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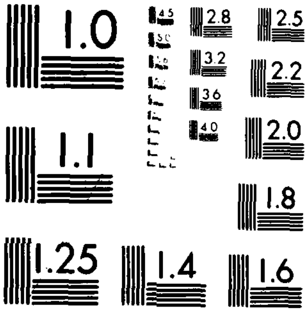

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REPORT NAEC-92-132

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EFFECT OF LUBRICANT CONTAMINANTS ON WEAR RATES OF LUBRICATED COMPONENTS

Handling and Servicing/Armament Division
Ground Support Equipment Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

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EFFECT OF LUBRICANT CONTAMINANTS ON WEAR RATES OF LUBRICATED COMPONENTS

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Particulate Contaminant Parameters		Component Testing Methods and Systems	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of a study on the effect of particulate contamination upon the wear rates of oil-wetted components normally used in lubrication systems. The components primarily considered were rolling-element bearings, journal bearings, gears, and reciprocating seals. Particulate contaminant parameters are discussed. Component testing methods and systems are presented for each critical wear component category.

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SUMMARY

The need for determining the effect of particulate contaminants on wear rates in lubricated components is realized. This report is the first phase of a multi-phase program aimed at understanding the phenomenon. The objective of the first-phase effort is to accumulate pertinent information concerning wear in lubricated components through an extensive literature search, thus providing a strong background in component wear. It is felt that this background complemented by the contaminant sensitivity expertise in hydraulic components at the Fluid Power Research Center will produce valuable results from actual lubricated component tests.

The testing of the lubricated components will be the second-phase effort of this program. The components of interest are both oil-wetted and sensitive to particulate contaminant. These components will be referred to as critical wear components. Critical wear components include bearings, gears, and sliding contacts. The wear and performance shall be the parameters emphasized in testing. Wear particle analysis, Ferrography, and particle counting will determine the amount of wear induced by the entrained particles. Performance monitoring, such as vibration and temperature, will be included. The particle injections into the lubricating medium will be controlled with respect to particle size, concentration, and composition. For example, to determine the effect of concentration on wear rates, particle size and composition would be held constant as the concentration was varied.

Ball bearings were selected as the first critical wear component to be tested in the second-phase effort. A test program matrix is presented with a discussion to illustrate the approach to be employed. Although the procedure presented is specifically for ball bearing tests, the basic concept of the procedure will be implemented in all component test programs.

Test result evaluation will involve the correlation between wear rates (as determined Ferrographically), performance parameters, and particulate contamination. It is felt that the purpose of the correlations is to provide the machinery operator, the technician, and the engineer with valuable information. That is, the effect of particulate contaminants on lubricated components shall be determined to allow increased reliability and performance of these common and necessary components.

PREFACE

This report was prepared by the staff of the Fluid Power Research Center of the Division of Engineering, Technology and Architecture, Oklahoma State University of Agriculture and Applied Sciences. The study was initiated by the Naval Air Engineering Center at Lakehurst, New Jersey. Authorization for the effort reported herein was granted under Contract No. N68335-76-C-2280.

The effort reported herein was effectively monitored by the Naval Air Engineering Center whose counseling and direction were significant in the successful completion of this effort. The studies were conducted under the general guidance of Dr. R. K. Tessmann, Program Manager of the Fluid Power Research Center (formerly), with consultation from Dr. E. C. Fitch, Center Director. The findings and conclusions are presented in this final report.

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I. INTRODUCTION

A. A great many of the modern fluid systems can be properly classified as power transformers. For example, internal combustion piston-type engines fall into this category. By briefly tracing the power through the engine, the relevant characteristics of power transforming systems can be highlighted. Fuel and air are brought into the engine, where they are burned. The burning fuel creates pressure which can be transformed into mechanical power by permitting the expanding gases to act on the face of the pistons. The force exerted on the pistons is transferred to the output shaft of the engine through a crank arrangement.

B. In order to operate efficiently, the piston-type internal combustion engine must incorporate a means of effectively sealing the piston in the combustion chamber while still permitting it to reciprocate. In addition, the various connecting points between the piston and the crankshaft must include some appropriate bearing design. Each of these critical areas is characterized by surfaces in relative motion, high loading, and high relative velocities. In order to improve efficiency and reduce friction and wear, these crucial components are supplied with lubricating fluid. The objective of the lubrication is to prevent surface-to-surface contact within the components by providing a fluid film upon which the mating parts "ride."

C. An auxiliary circuit is incorporated in most power transforming systems to provide a supply of the lubrication fluid. The high relative velocity and loading in the lubricated component produces considerable heat, which is carried away by the lubricant. Therefore, the auxiliary circuit must include a means of cooling the lubricant. In addition, this circuit must incorporate a filter to remove the particulate contaminants which will become entrained in the lubricating fluid during machine operation.

D. Particulate contaminants enter the lubricating fluid in three ways. The debris from the wear processes taking place within the mechanisms becomes entrained and accounts for one source of particulate contaminants. This is normally called generated contamination. A second source is the external contaminant which enters through seals, breathers, etc. This is commonly referred to as ingested contamination. The third source is often overlooked in the discussion of contaminant sources - fabrication residue. This is the contaminant left in the system when it is assembled or repaired. These three sources of contaminants are not independent. That is, when a system exhibits high ingestion rates, wear rates normally increase and more generated contaminants enter the lubrication fluid.

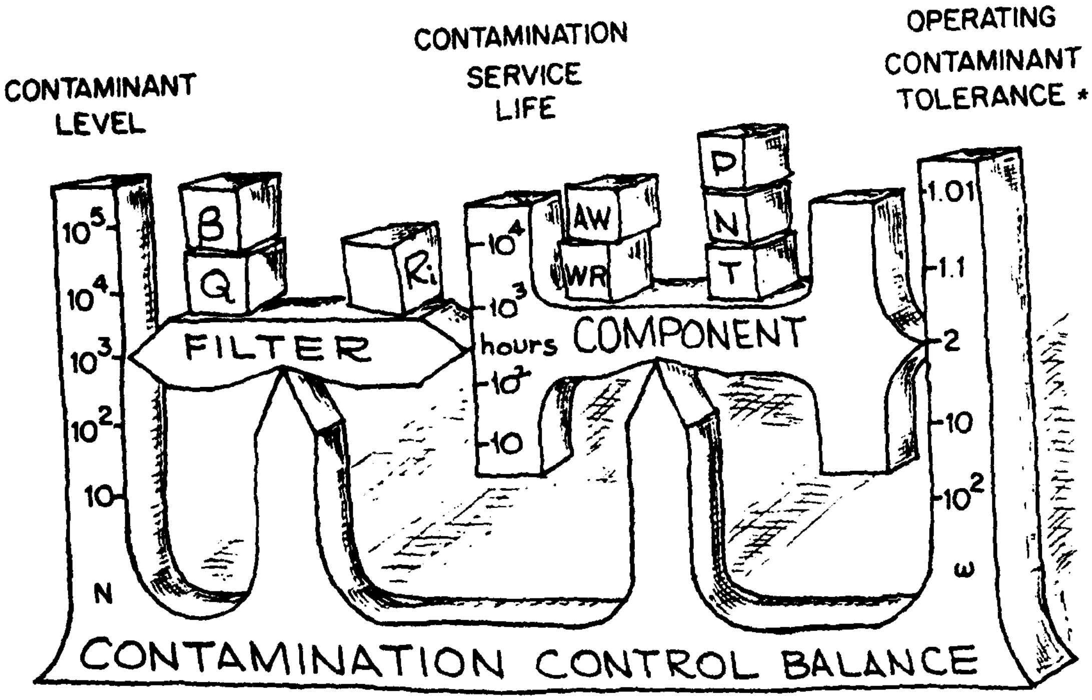
E. In recent years, it has become increasingly apparent that the wear rate of fluid system components is greatly accelerated by the presence of particulate contaminants entrained in the fluid. A great deal of work on the contaminant sensitivity of hydraulic components conducted by the Fluid Power Research Center (FPRC) at Oklahoma State University has shown that a significant improvement in reliability, maintainability, and wear life can result from the proper control of particulate contamination in the system fluid. In some of these efforts, contaminant wear was evaluated by measuring the degradation in performance of the component under a carefully regulated contaminant environment. In other projects, the contaminant wear was measured through both performance degradation and the Ferrographic oil analysis system. This work has shown that Ferrographic analysis data can be correlated to performance degradation through proper consideration of the wear mechanism involved. Based upon these studies, it can be concluded that particulate contamination is definitely a catalyst in wear processes.

F. In many previous studies and applications of contamination control, progress has been impeded by the perplexity created by parameter interaction. Only in the last few years has sufficient insight been gained to recognize the controlling parameters of a system and to adequately describe the influence of each parameter upon the system as a whole. The contamination control balance illustrated in Figure 1 and discussed in this report is an attempt to convey the nature of the parameter interaction in a pictorial form. The balance should prove valuable to the reader in assisting him to understand the many principles of contamination control.

G. Fluid contamination control is practiced for only one purpose--to obtain an acceptable contaminant service life, reliability, and maintainability for all components comprising a hydraulic or lubrication system. From a contamination control standpoint, it is now realized that these three aspects depend almost entirely upon two factors--the contamination level of the system fluid and the contaminant tolerance of the system components. Thus, as the contamination control balance implies, to obtain a given contaminant service life for a system, it is necessary to achieve a proper balance between the contamination level of the fluid and the contaminant wear resistance of the components.

H. The contamination level of the fluid is controlled by the particle separation capability of the filter given by the filtration ratio (β), the flow rate (Q) of fluid passing through the filter, and the rate (R_i) at which particulate contamination enters the system fluid. The tolerance level of the system is dependent upon the wear resistance (WR) of the component to contaminant attack. Standard contaminant sensitivity tests can be used to demonstrate the differences in wear resistance of the various components. The anti-wear (AW) characteristics of the system fluid will also play an important role in establishing the contaminant tolerance of components in general. Finally, the severity of the operation denoted by pressure, speed, and temperature (P, N, T) can greatly alter the capability of some components to function satisfactorily in a contaminated environment. The contamination control balance shown in Figure 1 depicts how each of these parameters influences the contaminant tolerance level of the fluid system.

I. The work accomplished in the TRI-Services Research and Development (R&D) Oil Analysis Program sponsored through the Naval Air Engineering Center, Lakehurst, New Jersey, further substantiated the concept that particulate contaminants in the fluid of lubrication systems are truly wear catalysts. In this program, ball bearings were tested in an extremely clean environment, and the results indicated a life in excess of 40 times their calculated expected life. In other ball-bearing tests, failure was artificially induced by the introduction of a Vickers hardness indent into the inner race of the bearing to simulate the dents caused by contaminants. In these tests, failure occurred in a much shorter period, although the bearings still exhibited lives in excess of the



* *Tolerance equals reciprocal of scale.*

Figure 1 - Contamination Control Balance

computed life. However, full realization of the detrimental effects of contaminants in an oil-lubricated system/equipment has not been identified up to this time. Due to the nature of oil-wetted components, the effects of contaminant-related wear are much more subtle than in hydraulic systems.

J. The results of previous studies dealing directly with the contaminant-accelerated wear phenomenon certainly indicate the severity of the problem. Without a doubt, there is sufficient evidence to suggest that better knowledge concerning the effects contaminants have on the wear rates of lubricated components could lead to improved life, reliability, and maintainability. Of course, one solution to the problem of contaminant related wear is to remove the contaminants. However, complete removal of contaminants from a lubrication fluid is not a practical consideration at this time. Hence, in order to provide cost effective contamination control, it is necessary to identify the wear processes involved and the influencing parameters.

K. In order to obtain the required technology associated with the influence of particulate contaminants upon the wear rates exhibited by lubricated or oil-wetted components, it is necessary to define the contaminant variables of interest. In addition, the critical components subject to contaminant wear in a lubricated system must be identified. Also, since performance is very important, a wear-related performance parameter must be determined for all contaminant-sensitive components. Thus, it is necessary to define the properties of the contaminants normally entrained in lubrication fluids, identify the contaminant-sensitive components in lubrication systems, and determine appropriate performance parameters associated with these components.

L. Since the crucial wear components in lubricated systems must be fully enclosed during normal operation, it is virtually impossible to study the contamination-related wear phenomenon directly under realistic conditions. Therefore, this program will rely upon the experimental evaluation of wear rates of critical oil-wetted components under controlled contaminant environments through both wear particle analysis techniques and performance degradation. The use of this approach requires the development and design of component test fixtures to insure the realistic conditions desired. In addition, the means of measuring the wear rates associated with any given contaminant environment must be given careful consideration. Furthermore, a test system must be developed and fabricated to provide the realistic loading and operating condition for the test component.

M. The primary objectives of this first phase of effort associated with the goal of investigating the influence of particulate contaminants upon the wear of oil-wetted components are to: (1) explore and document previous efforts, (2) develop and design critical component test fixtures relative to lubricated systems, (3) formulate suitable test procedures to produce meaningful results, and (4) formalize techniques for evaluating test results. The remaining sections of this report discuss the progress made to date and outline the activities which are yet to be completed.

II. TECHNICAL BACKGROUND

A. BACKGROUND

1. While there has been a considerable amount of work reported on the effect of contaminants upon the wear of oil-wetted components, it is extremely difficult to apply the results of these efforts to the design and protection of specific components. In exploring the published information, it was found that the vast majority of research work which could be used to define necessary contaminant protection has been directed toward hydraulic components and systems. However, in considering the wear surfaces and mechanisms in hydraulic components as compared to those in lubrication components, a great deal of similarity can be found. Therefore, it is felt that the contaminant wear concepts developed for hydraulic applications can provide an effective background for studies of contaminant-accelerated wear rates of lubrication components.

2. It must be realized that the effect of entrained particulate contamination in both oil systems and hydraulic systems is to increase the wear rate and shorten the service. However, in hydraulic systems, other effects can also be traced to the presence of particulate contaminants. Valve spools which are an integral part of most hydraulic systems can stick from a silting action of the contaminants. Such events will obviously influence reliability and maintainability but are not directly related to wear life. In oil-wetted components, the reduction in life due to increased wear is by far the most prevalent effect and therefore renders the observed result to be of a long-term nature. The more apparent effect of particulate contamination in hydraulic systems has resulted in considerable emphasis on contaminant sensitivity/filtration.

B. CONTAMINANT PARAMETERS

1. Particulate contaminants have been extensively investigated during the last decade. From experience at the FPRC and a careful appraisal of the literature, it has been concluded that there are four critical parameters associated with particulate contamination entrained in a fluid system (size distribution, concentration, shape, and composition) [1,2,3,4,5,6,8,9,10,11,12,13,14,15]. These parameters are used to accurately describe contaminants from all three sources (generated, ingested, and fabricated residue). Although some progress has been made toward understanding the effects of these critical parameters, little emphasis has been placed upon "realistic" contaminant testing of actual oil-wetted components, especially rolling-element bearings [16,17]. A major portion of particulate contaminant testing has been limited to the use of simple configurations, such as metal specimens on dry abrasive paper or two rubbing planar samples in an oil bath [8,9,12]. The bearing which has been the subject of most research effort with regard to contaminant sensitivity is the journal bearing. Most of this research was carried out before the introduction of modern methods of wear particle analysis (such as Ferrography) [14,15]. The results of these efforts are usually given in terms of volume of material removed versus the various test variables (e.g., concentration,

particle size, load, speed, etc.). A correlation between this empirical information and oil-wetted components in realistic environments is necessary in the design of oil-wetted components and lubrication systems.

2. The first two contaminant parameters, size distribution and concentration, have received serious consideration by most researchers in the contaminant wear area. These two parameters are, by general consensus, the most influential in the wear process and are by no means mutually exclusive [2,3,5,7,11,14,16]. Studies have shown that, with a constant particle size exposure, the wear rate of the component increases with concentration increases [2,3,5,11,17]. In addition, it has been found that the ratio between wear rates and concentration will increase as the particle size increases (Figure 2). Figure 2 has three particle sizes represented on a wear rate versus concentration graph. The D_1 curve represents the smallest particles (e.g., 0-10 μM), and D_3 curve represents the largest particles (e.g., 0-80 μM), and the D_2 curve represents some particle size between 0-60 μM. Although the plot is generalized, it illustrates the correlation between wear rates, particle size, and concentration. The correlation between these parameters has proved to be useful in predicting component life and performance degradation of various hydraulic components.

3. The other two contaminant parameters, composition and shape, have received little study in comparison with concentration and size distribution [6,10,12]. The testing of the effect of particle composition on wear has been limited to abrasive-coated papers (sandpaper, emery, cloth, etc.) rubbing against a test specimen, usually a metallic rod or disk [12,18,19]. Like the dependency between particle size and concentration, composition and shape are also dependent on each other as far as the induced wear is concerned. Actually, there are two types of dependencies between composition and shape. The dependence of a particle's shape on its composition is illustrated by a sharp-edged crystalline solid such as silica. The severity of wear generated by particles of a given shape also depends on composition. For example, a sharp, hard particle is a far better cutting tool than a sharp, soft particle or a round, hard particle. The contaminant sensitivity of a component has been found to be dependent on its material hardness relative to the particulate contaminant hardness [12,15,18,19,20]. In studies on the wear of metals by particles, it was found that particles harder than the component materials induce more critical surface damage than particles softer than the component material [18,20].

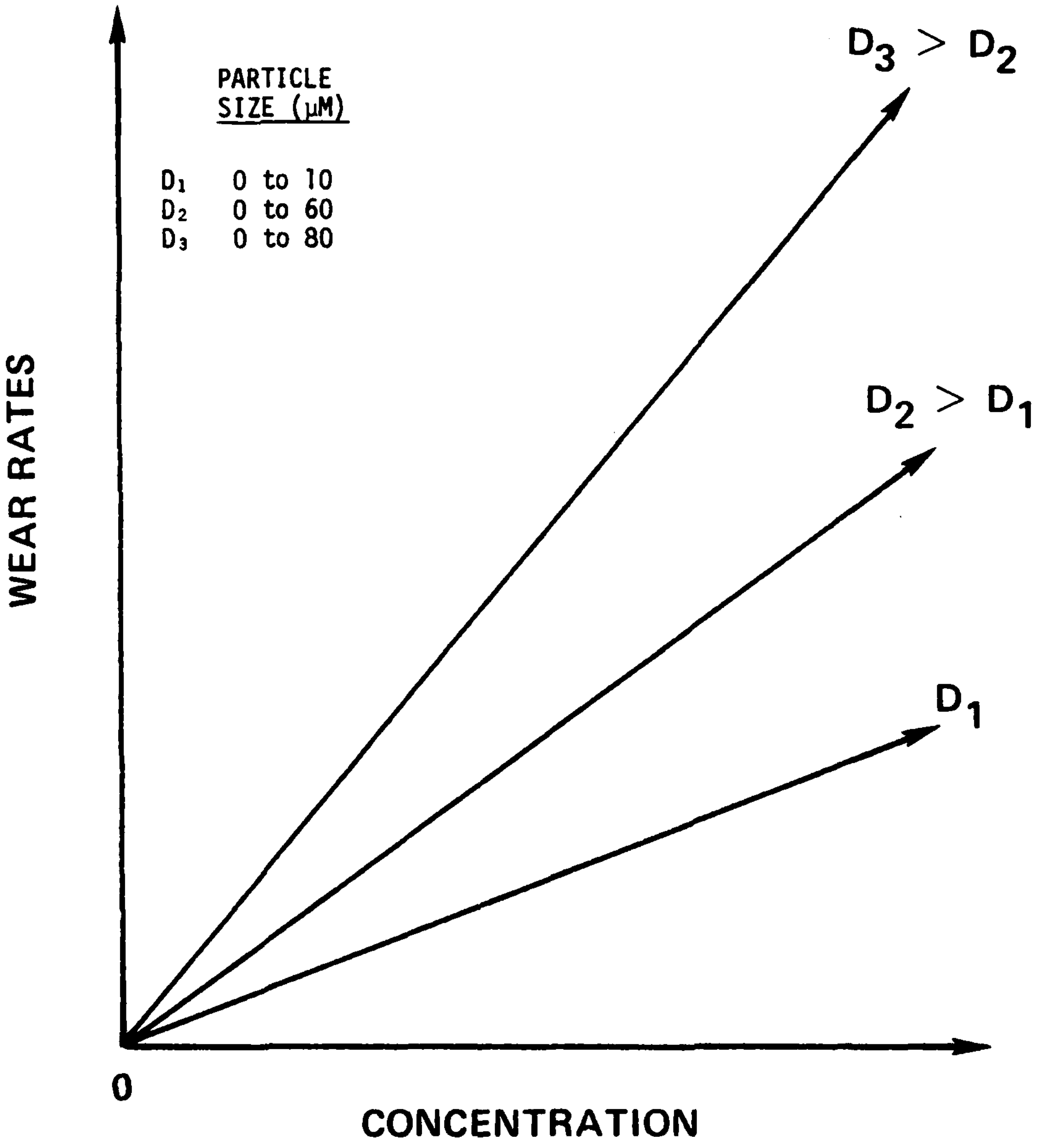


Figure 2 - Generalized Plot Illustrating the Effect of Contaminant Size and Concentration on Wear Rates of Critical Wear Components

III. CRITICAL WEAR COMPONENTS

A. Machine components which are both oil-wetted and sensitive to particulate contaminants shall be considered to be critical wear components. Consequently, bearings, gears, and sliding mechanisms will be included as critical wear components. In most applications, these components will be exposed to particulate contaminants entrained in the lubricating medium. Although the concentration, size distribution, shape, and composition of the entrained particles will vary, particles will certainly be present in the majority of lubrication systems. Due to this commonly shared parameter of exposure to particle-entrained environments, the effect of particulate contaminants on the critical wear components must be included in the discussion of their individual characteristics.

B. The functions of the critical wear components are different in reference to duties performed. However, basic characteristics may be commonly shared. Bearings function as the component for supporting a rotating load and gears function as power transporters. Although the functions are different, both components commonly share extreme pressure lubrication as critical surface separation. Lubrication type is one of the characteristics to be considered in the contaminant-induced wear analysis of critical wear components. Descriptive and useful characteristics of the components include surface hardness, material, surface finish, loading, lubricant, etc.

1. BEARINGS

a. Bearings, the critical wear component for supporting rotating loads, are divided into two groups - rolling-element and journal. Journal bearings typically employ a hard journal rotating within and supported by a softer material. This softer material is referred to as the bearing and may be brass, lead-babbitt, silver, or any one of many bearing materials. The selection of this material is dependent upon the application. One property that is often considered is a property solely available to journal bearings and referred to as embeddibility. Embeddibility is the ability of the bearing material to embed harmful abrasive particles below the bearing surface [20,21,22]. Roach did a study on the embeddibility of various materials and bearing grids in journal bearings exposed to a particulate-contaminated lubricating fluid [14]. Roach's studies did concern the effect of particulate contaminants on journal bearings; however, there was no actual wear analysis of the bearing with respect to the particulate contaminant. Several journal bearing studies have attributed various types of damage to particulate contaminants entrained in the lubricant, but no controlled experiments have been noted to date [23,24,25].

b. Rolling-element bearings, the second of the bearing group, include roller bearings and ball bearings. The test effort will be broken up into the individual lubricated component tests. The first component to be tested is ball bearings. A more detailed discussion of ball bearings will be presented as an introduction to the ball bearing test effort. Although roller bearings are not specifically typified by a certain rolling-element shape, as are ball bearings by spherical rolling elements, basic characteristics are common among rolling-element groups. Should any difference be significant, it will be noted.

c. Ball bearings are advantageous in application because of the high work efficiency exhibited (roughly 99%) and the long lives under recommended working conditions (temperature, lubrication, loading, and speed). Sensitivity to adverse conditions, such as overloading and excessive temperatures, causes only about 15% to fail due to normal fatigue wear [26]. Fitzsimmons, Clevenger, and Cave of the Timken Company have done controlled studies on the effect of particulate contaminants on tapered roller bearings, typical of those found in automobile differentials [16,17]. The results were similar to those of hydraulic contaminant sensitivity tests in relationship between wear and concentration. Figure 3 illustrates the correlation between particle concentration in the lubricant and bearing wear [16]. The wear-to-particle-size relationship varied somewhat from typical hydraulic particle sensitivity in that the bearing wear decreases when exposed to 30-40 μM test dust relative to 20-30 μM dust. The bearings were tested in closed housings and were lubricated by 250 cc non-flowing lubricant with the desired contaminant concentration level. This method does simulate contaminants entrained in fluid; however, components in service are exposed to constant contaminant ingression. That is, the components are constantly exposed to all "fresh" particulate contaminants.

d. The surface damage of ball bearings due to particulate contaminants has been generally agreed upon as either bruises or dents. General sources claim that "dents" and "bruises" on the races are the result of three-body contact in the bearings (specifically, the balls, races, and the contaminant [12,26,27,28,29,30,31,32,33,34,35,36,37,38]). Others expand the induced damage further into two types - bruises and lapping. That is, larger particles will bruise the races; whereas, small particles will "lap" the race surface [27]. Surface smoothness of rolling contact elements is a critical factor in the wear process, due to its effect on contacting surface lubrication as studies by Scott have shown [24,25,39].

2. <u>GEARS.</u> Gears, the second critical wear components, have received little or no study with respect to particulate contaminant sensitivity. Damage in the form of dents has been attributed to particulate contaminants which might be expected because of the high-pressure lubrication (elastohydrodynamic), which is also typical of ball bearings [40,41]. Similarly, surface finish of gear teeth is also considered a substantial factor in gear wear. The surface hardness of gears varies far more than that of ball bearings, which are usually a Rockwell C hardness of 57-63. Surface hardness is generally determined by the duty to be performed. For example, gears for long-life gear applications usually have hardened teeth, due to improved mechanical properties over those of softer teeth. Temperature also plays an important role in gear wear. As tooth temperature rises, the ability of the lubricant to separate the teeth decreases; consequently, clearances diminish, allowing scoring and scuffing to occur [21,22,41,42]. It is felt that this decrease in clearance will also magnify the effect of particulate contaminants on the gear sets. Particles that would normally pass between the teeth with some slight contact would be "smashed" in the extremely small clearances. The damage resulting from this phenomenon is usually visually detected as dents, lapping, or ridges [27].

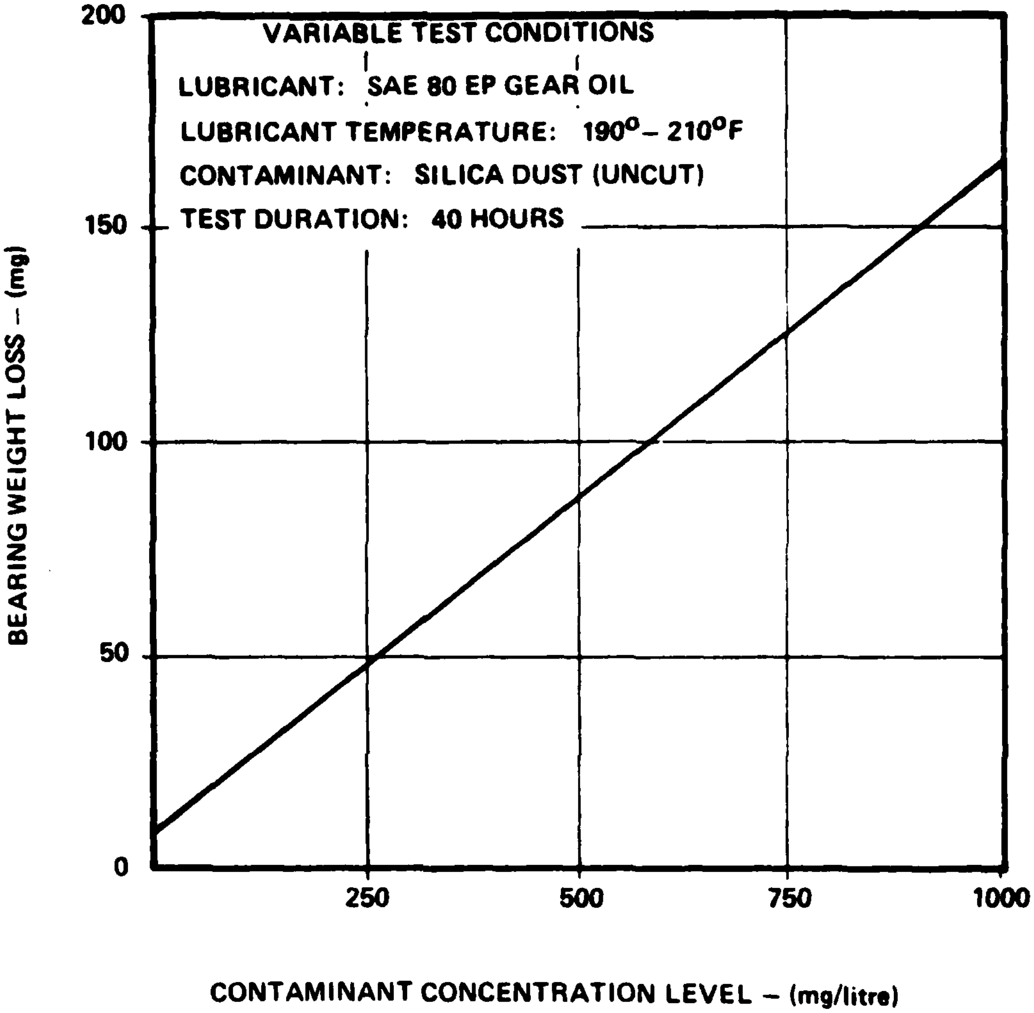


Figure 3 - Relationship of Bearing Wear to Contaminant Concentration Level

3. SLIDING MECHANISMS. Sliding mechanisms are those mechanisms which have sliding relative motion, but do not have a primary function such as bearings or gears. Sliding mechanism functions include power transduction (such as the change from rotational motion to linear motion, as that of a cam and lifter arrangement). Another function involving sliding mechanisms is the piston ring/cylinder arrangement typically found in internal combustion engines. The literature search produced no information of significance to cam/lifter interfacial wear related to particulate contaminants entrained in the fluid. Piston rings, however, have received some study with respect to particulate contaminant sensitivity [43,44]. Radioactive cast-iron piston rings were used in the contaminant sensitivity tests, and the wear rates were determined by the amount of radioactive material generated and deposited in the crankcase oil. As would be expected, the wear rates of the piston ring increased with contaminant concentration, illustrated by Figure 4. Ferrographic analysis of the wear particles generated in such a test would give an indication of the wear process involved. An understanding of the phenomenon would complement such a study.

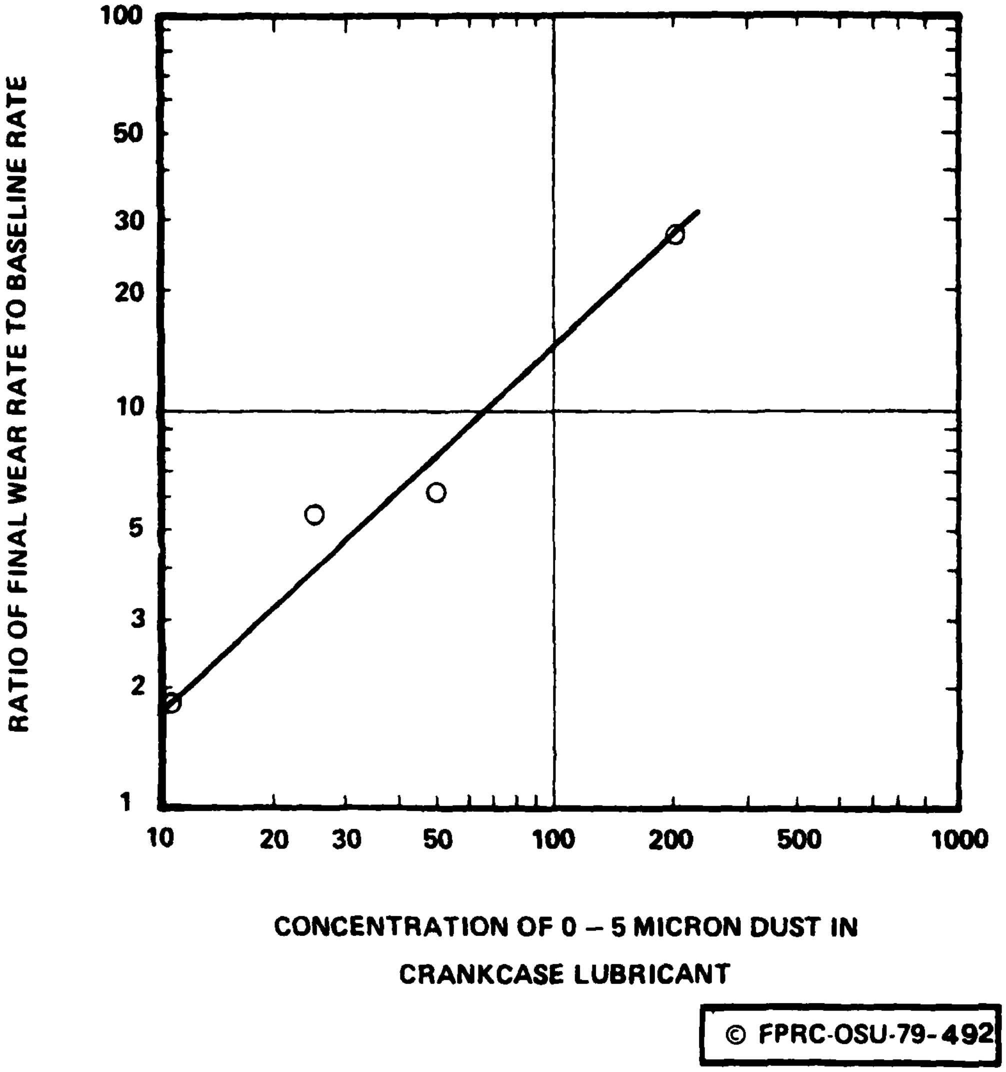


Figure 4 - Effect of 0-5 μM Dust Concentration in Crankcase Oil on Piston Ring Wear Rates [43]

IV. WEAR-RELATED PERFORMANCE PARAMETERS

A. For purposes herein, wear may be defined as the deterioration of critical surfaces within an oil-wetted component. Component wear can manifest itself in two ways: (1) dimensional changes of the component and (2) performance degradation of the component. There is obviously a dimensional change of the wearing surfaces in the component. Such dimensional changes are the result of the wearing away of material and rarely a transfer of material from one surface to another [44]. The measurement of the amount of debris generated during a wear process can be useful in determining the degree of wear in a critical wear component when subjected to a contaminant environment. The failure of a component, however, has not been defined in terms of wear debris generation. Rather, a component is considered failed when its performance degrades to a point where it no longer functions effectively. Performance degradation in terms of machine function may be under constant observation by the operator. The degradation in function can be expressed in terms of wear-related performance parameters (such as vibration, noise, temperature, or power consumption). Since the failure of a critical wear component is related to its performance, the primary wear-related performance parameters are critical in determining the effects of particulate contaminants on those components.

1. BEARINGS

a. Wear-related performance parameters generally associated with journal bearings are heat, power consumption, and vibration. Performance of a journal bearing is dependent on the fluid film separation of the bearing and journal. Because the film is very thin, particles which are often entrained in the lubricating fluid will essentially "plough" the bearing surface. This "ploughing" process often forms a valley from the oil hole to the edge of the bearings (Figure 5). Should these valleys become big enough, oil flow that would normally act as the fluid film, separating the bearing and the journal, would follow the tracks and hinder the formation of fluid-film separation [15]. Particles embedded in the bearing may cause a discontinuity in the oil flow and the fluid film. This discontinuity can manifest itself in the form of cavitation and lead to intensive vibration [45,46]. Insufficient fluid film is necessarily accompanied by excessive friction and heat. The increase in power consumption by the bearing is caused by an increase in friction. Friction is also the basis for heat increases, which may be observed as higher machine temperature.

b. Wear-related performance parameters for rolling-element bearings are heat, power consumption, and vibration. The high load-to-contact-area ratio between the rolling elements and the races resulting in minimal fluid film separation makes rolling-element bearings sensitive to particulate contaminants typically found in lubricating oils [27,28,31,33,34,47]. As clearances increase due to the wear process, the freedom for movement of the inner race relative to the outer race results and frequently vibration occurs. Vibration, often detected by machine operators as noise, causes increased element loading and, consequently, accelerates the wear process. Power consumption, a function of friction, will increase with loading and/or with deficiencies of fluid-film separation due to scarred races and rolling elements [28,29,31,33]. As bearing temperatures increase with friction, the lubricant loses its effectiveness, which produces an accelerating effect. For example, a bearing cage test involving the exposure to one type of oil at 300°F resulted in a hard carbonaceous deposit, which could have detrimental effects on bearing performance and lead to failure [34]. The conclusion that can be drawn with regard to rolling-element performance parameter degradation is the common dependence on wear and, conversely, their indication of component wear.

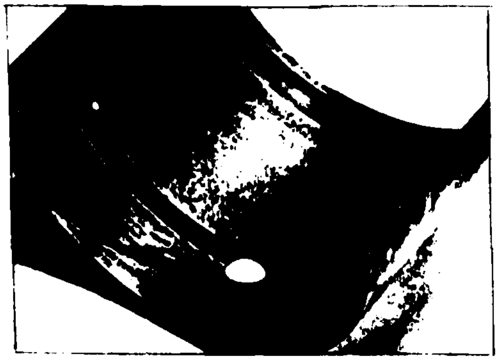


Figure 5 - An Example of an Eroded Valley in the Bearing Caused by Abrasive-Entrained Oil [15]

2. GEARS. The second critical wear component, gears, has the wear-related performance parameter of backlash in addition to heat, friction, and vibration. Backlash (an increase in tooth-to-tooth clearance) is a result of tooth wear and may be observed as "jerky" or delayed reactions to directional or load changes. Vibration (due to tooth misalignment and often accompanied by backlash) may be observed directly as machine vibration or indirectly as noise [48,49]. The sliding action of the gears induces friction; and, consequently, heat is produced, which must to some extent be dissipated by the lubricant. Should the heat be too severe, the lubricant will lose its effectiveness, leading to catastrophic failure [21,50]. The wear-related performance parameters of gears are, in summary, heat, friction, vibration, and backlash.

3. SLIDING MECHANISMS. Sliding mechanisms, seals, and cams have two individual sets of performance parameters. Cams will exhibit an increase in heat with friction and will lose the effective lifting travel as the material wears. Reciprocating seals have one major wear-related performance parameter and that is leakage. Reciprocating seals in the form of piston rings will cause a decrease in engine output power, which may be accompanied by an increase in exhaust smoke and a change in lubricant color due to "blow by." Performance degradation of both cams and reciprocating seals can have a detrimental effect on an engine's performance.

V. DEVELOPMENT AND DESIGN OF CRITICAL WEAR TEST MECHANISMS

A. Previous efforts have determined that ball bearings, roller bearings, gears, and sliding contacts are the major wearing components in oil-wetted systems. Thus, it will be necessary to develop and design a test fixture for each of these critical wear components. If only radial bearing loads are considered, it is possible to design a test fixture which can be used to evaluate the contaminant wear of either ball or roller bearings. Figure 6 shows a schematic of a proposed bearing test fixture designed to expose bearings to a controlled particulate contaminant environment as well as a controlled radial load. This fixture is unique in that three bearings are tested simultaneously by taking advantage of the action and reaction characteristics of the loading arrangement shown in Figure 7. As can be seen in Figure 6, the direct load is imposed on the center bearing, while the two support bearings are subjected to the reaction load. Thus, the actual loading on the support bearings can be varied by the placement of them at unequal distances from the center bearings. Each bearing (the center bearing and both support bearings) is contained by individual housings. The housings could be fabricated to accept different size bearings as well as either ball or roller bearings. The configuration of the housing is such that the lubrication fluid is forced into the cavity on one side of the bearing, flows through the bearing, and is discharged into the cavity on the opposite side of the bearing. Of course, in order to provide each bearing with a controlled contaminant environment in the lubrication fluid and to be able to monitor wear through fluid analysis, a separate fluid system will be required for each bearing. However, the testing time saved by evaluating three bearings simultaneously is expected to more than offset the additional equipment costs.

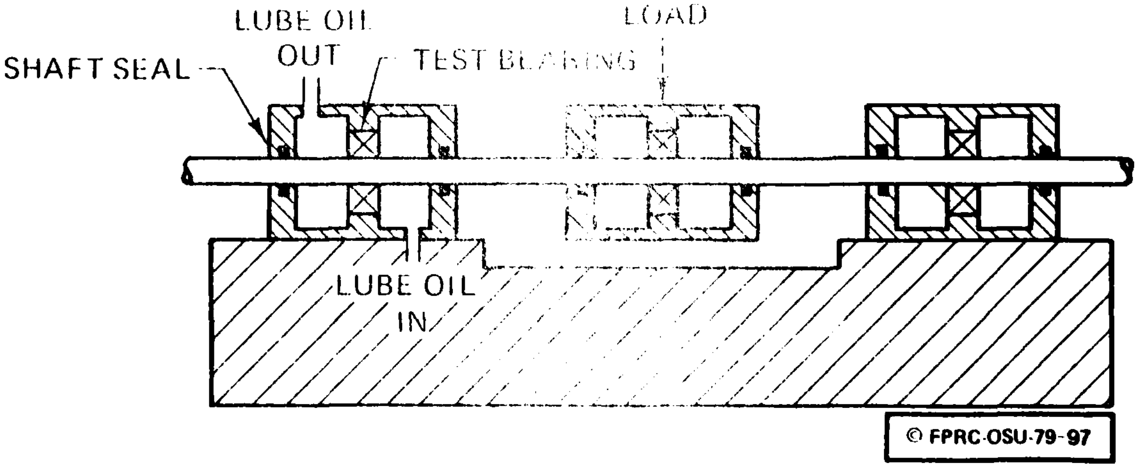


Figure 6 - Bearing Test Fixture Schematic

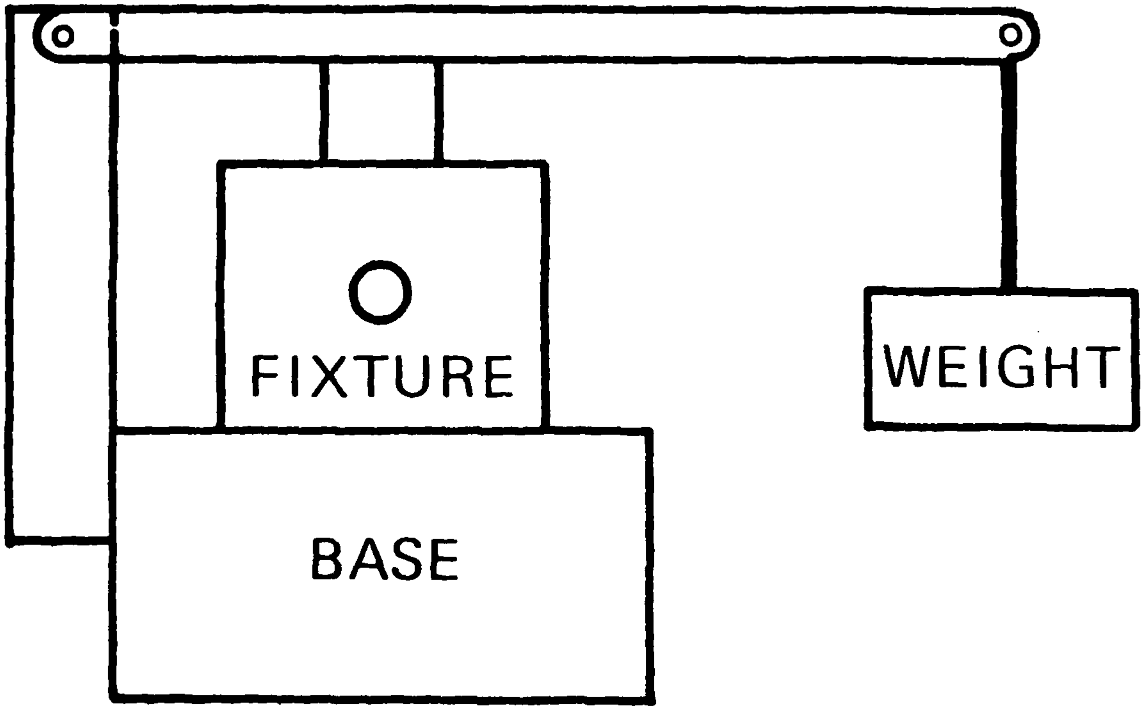


Figure 7 - Bearing Test Fixture End View

B. A proposed fixture to evaluate the wear of gears in a contaminated fluid environment is shown in Figure 8. The design of this fixture is fairly straightforward, consisting of a drive gear and a load gear supported by appropriate bearings. The fluid seals are located inside the bearings to prevent the contaminated lubricant from injuring these separately lubricated bearing units. Another critical factor in the decision to place the shaft seals inside the bearings is due to the fact that it is necessary to keep any wear debris which may be generated in these bearings from becoming entrained in the circulating lubricant and masking the debris generated by the gear set. The housing which contains the gear lubricant is designed to permit a continuous circulation through the chamber. This allows excellent control of the entrained contamination by external conditioning equipment. In addition, the operating temperature of the wear mechanism can be regulated by the temperature of the circulating oil.

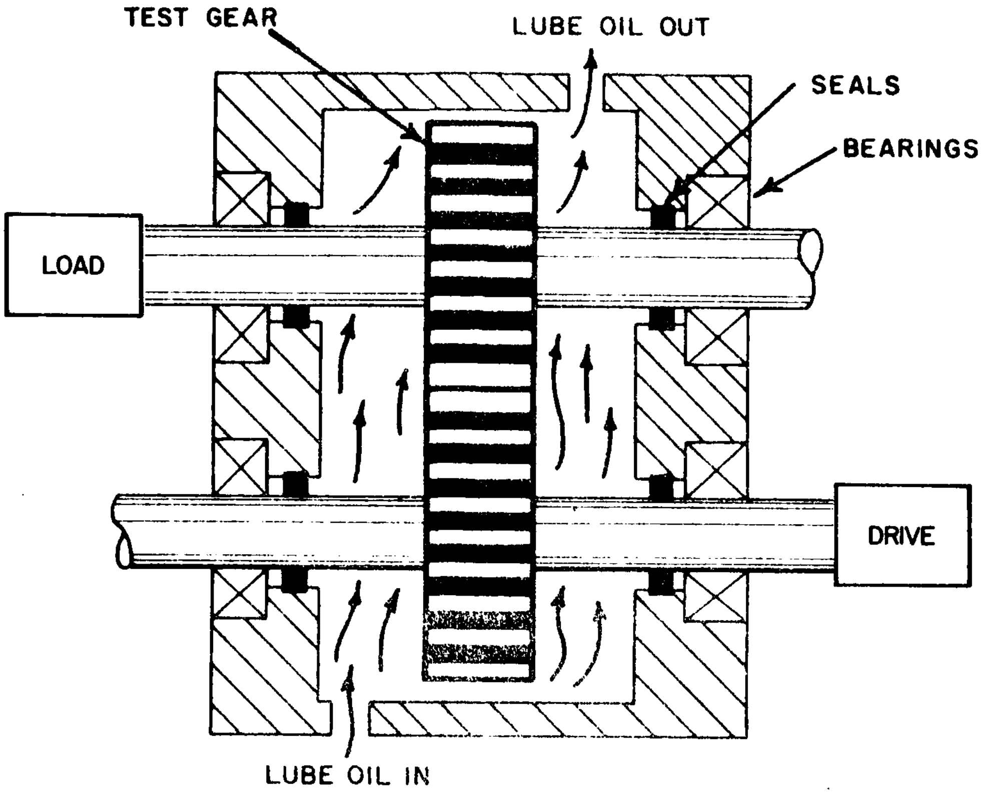


Figure 8 - Gear Test Fixture Schematic

C. A sliding contact mechanism is, without a doubt, the most difficult test fixture to develop with realistic simulation of the operating characteristics of the lubricated component. The most notable example of this type of component is the piston ring assembly of the internal combustion engine. Although the objective of this component is to seal gases in the combustion chamber, it is felt that the test fixture should not include actual combustion, since by-products of combustion could become entrained in the lubricating fluid and could interfere with the debris analysis. However, with such reciprocating motion, realistic pressures and temperatures will be difficult to create in the laboratory. The proposed test fixture for the sliding contact component is shown schematically in Figure 9. The reciprocating motion of the piston and ring assembly is provided by a push rod/cam arrangement, while a return spring is incorporated to insure that the cam follower remains in contact with the cam. The piston ring and barrel would be fabricated according to the specifications of commercial piston engine manufacturers. The lubrication fluid would be sprayed on the bottom side of the piston to simulate the action normally found in internal combustion engines. This oil spray will wash the wear debris from the barrel walls. Sufficient circulation would be maintained during the operation of the test fixture to insure that the wear debris will stay entrained. The temperature and contamination level of the circulating lubrication oil can be controlled by an appropriate test system.

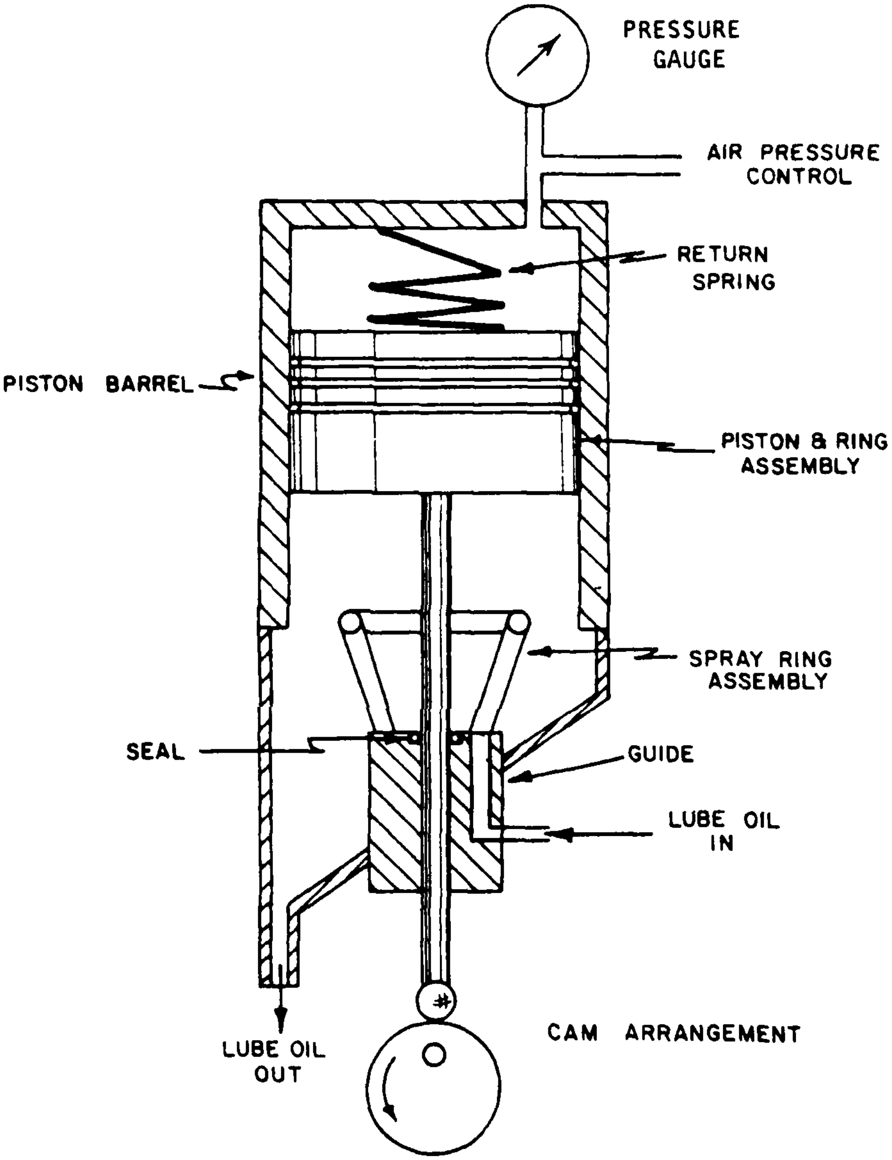


Figure 9 - Sliding Contact Test Fixture Schematic

VI. TEST SYSTEM DESIGN

A. The purpose of the test system in this program is to provide the appropriate fixture with properly conditioned lubrication fluid. This means that this system must include the following components:

1. A properly sized contaminant-insensitive pump to provide circulation
2. Appropriate temperature and pressure measuring devices
3. Contaminant-insensitive flow measuring means
4. Adequate control filters to provide a "clean" background environment
5. Contaminant injection facilities
6. Heater or heat exchanger for temperature control
7. Reservoir with a conical design to preclude contaminant settling and a diffuser for agitation
8. Provision for obtaining a representative fluid sample

The fluid recommended for use in these tests is one which conforms to MIL-L-23699 specification.

B. The proposed test system is shown in Figure 10. The circuit is designed to create turbulence in the connecting line to insure continued contaminant entrainment. Since the pressure normally encountered in lubrication systems is not great, it is felt that a contaminant-insensitive centrifugal pump could be utilized. In addition, the temperatures found in lubrication components are relatively high. Thus, it is assumed that the temperature controller would be a heater instead of a heat exchanger.

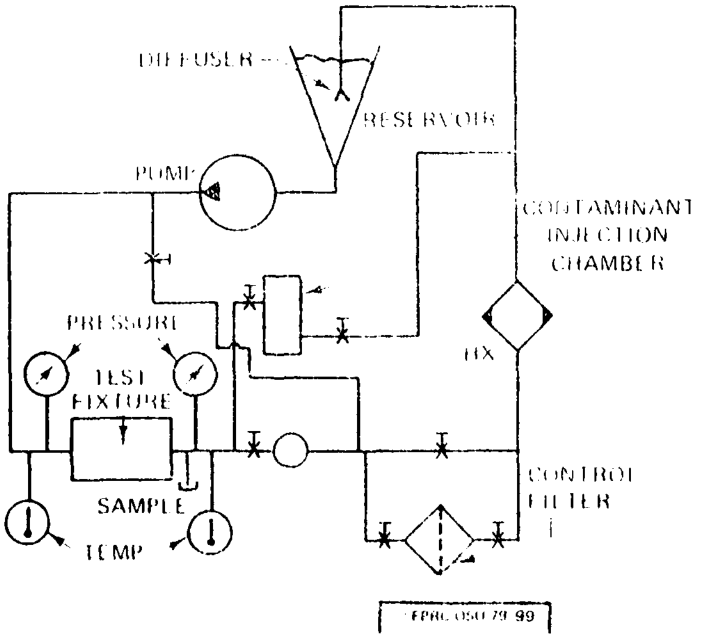


Figure 10 - Test System Schematic

VII. TEST STAND DESIGN

A. In the testing of lubricated components, it is necessary to have a mechanism to provide component function and a lubrication system. In the case of ball bearings, component function would require a rotating load. The lubrication system should provide an adequate lubricant supply with the capability of realistic particulate contaminant entrainment. The system incorporated in testing was described in the previous section and illustrated by the schematic of Figure 10. Three systems of this type will be required for the bearing tests, one for each bearing housing.

B. The rotating load for the bearings will involve a rotating shaft through the three test bearings of which the center bearing will have an applied load and the outer two will carry the reaction load. This configuration is illustrated by Figure 6. In order to impose a load of considerable magnitude (for example, 6,000 pounds) without the use of heavy weights, a lever mechanism will be implemented. For large loads, a possible compound lever system is illustrated by Figure 11. For lighter loads, however, a single lever arrangement would be preferable.

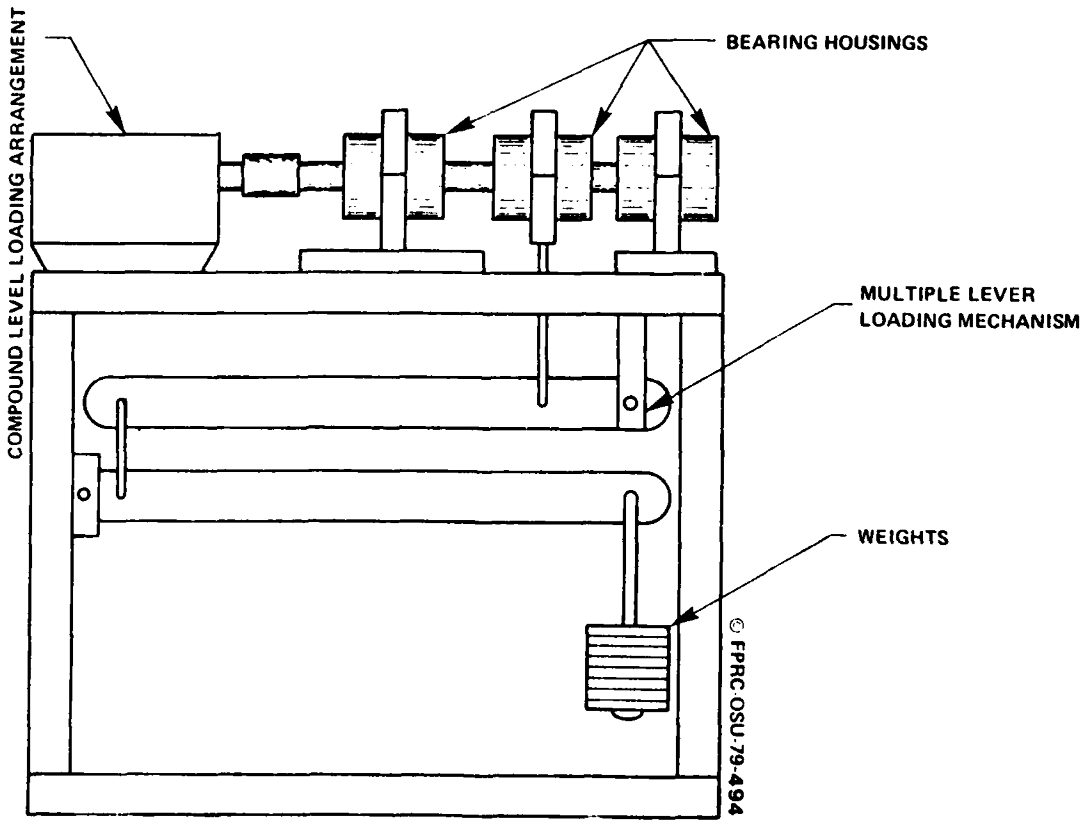


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Figure 11 - Bearing Test Rig Drive and Loading Arrangement

VIII. FORMULATION OF TEST TECHNIQUE

Obviously, each test fixture will require different test procedures; however, some general procedural guidelines will act as a basis for each component test. AC Fine Test Dust will be the primary test contaminant, and a metallic contaminant may also be used for comparative purposes. Wear particle analysis (consisting of Ferrographic analysis and particle counts) will be carried out on each oil sample extracted from the system. The performance parameters (heat, vibration, backlash, and leakage) will be monitored on the appropriate test fixtures.

A. THE TEST CONTAMINANT

1. The primary element in contaminant sensitivity testing is the test contaminant. Test contaminants must have the following qualities: (1) they must be a wear catalyst representative of contaminants ingressed in the field, (2) they must be separable into specific sizes, and (3) they must be reproducible for other testing. The test fixtures proposed herein will be subject to two contaminants--metallic and nonmetallic. A nonmetallic test contaminant used extensively with successful results at the Fluid Power Research Center is AC Fine Test Dust (ACFTD). The combination of a seven Moh hardness, good field contaminant simulation, and reasonable wear-catalytic properties makes ACFTD an excellent test contaminant.

2. The requirements for a good metallic contaminant are that it be: (1) relatively hard in comparison to the tested component, (2) nonreactive with the lubricants, (3) not easily confused with the contaminants generated by the test components, (4) preferably nonmagnetic for Ferrographic purposes, and (5) representative of metallic contaminants found in service. The metal dusts presently under consideration are titanium alloys. The tough characteristics make the titanium alloy dusts attractive candidates as metallic test contaminants. The final property left to be considered in test dust selection is the availability or producibility of the metallic powder.

B. BREAK-IN PERIOD. It is expected that each new component will need to be subjected to a break-in period. In the case of bearings, the amount of wear during the break-in process is dependent upon the manufacturing process and any misalignment of the bearings in the test system. Each bearing will be run for a maximum of five hours in order to eliminate early wear phenomena from the contaminant wear measurement. Lubricant samples will be extracted at 15-, 30-, 60-, 120-, 160-, 320-, and 640-minute intervals. During this period, in order to evaluate particle generation, control filters will be kept in the circuit to insure a "clean" fluid exposure. The control filters normally used in contaminant wear tests produce filtration ratios for particles greater than 10 micrometers of 1400-1500. No wear should be induced by generated particles during the break-in period. In addition, constant operating conditions (such as flow, pressure, load, and temperature) will be maintained during break-in in preparation for the contaminant tests.

C. CONTAMINANT INJECTION

1. Contaminant injections will begin after the break-in period without stopping the test system. There will be a total of three contaminant properties. They are: (1) contaminant concentration tests, (2) particle size evaluation tests, and (3) contaminant composition tests. The contaminant tests (shown in Table 1) will be conducted on three bearings using a 0-80 particle size, classified from ACFTD stock, and concentrations of 10, 20, 40, 80, 160, 320, and 640 mg/liters of contaminant. The best contaminant level for contaminant wear evaluation of the ball bearings will be selected based upon the results of the concentration tests. Once the critical concentration has been selected, particle size tests will be conducted on three bearings of each type. The particle size ranges to be used are: 0-5, 0-10, 0-20, 0-30, 0-40, 0-50, 0-60, 0-70, and 0-80 micrometers of ACFTD. Finally, one test will be conducted on a set of three bearings using the selected metallic contaminant in order to evaluate the effect of composition on ball bearing wear rates.

2. Past experience has shown that particulate contaminants lose their effectiveness after a period of time. In order to better simulate constant contaminant ingression found in the field, each particle size range and concentration would be subjected to the test mechanism for a limited period. Once the test component has been adequately exposed to a specific contaminant environment, the complete test system would be filtered to remove the contaminant. This filtering process permits performance readings to be made in "clean" oil and prepares the system for the next size range or for a new concentration. For example, assume that the test component has been exposed to a 50-mg/liter contaminant slurry of 0-10 micrometer particle size range. This contaminant will then be removed by the filtration circuit before introducing the next environment. Contaminant injections would be introduced to the test system upstream from the reservoir (illustrated in Figure 10). This will allow the contaminant slurry to mix thoroughly with the system before it reaches the component.

D. TEST FLUID. In order to insure that the contaminant-accelerated wear tests are as realistic as possible, it is necessary to use a test fluid which is normally used with ball bearings. One of the most important applications of ball bearings which is also of interest to the Navy is that of turbine engines. The fluid normally associated with such applications is one which conforms to the characteristic delineated in MIL-L-23699 specification.

TABLE 1 - BEARING TEST PLAN TABLE

TEST NO.	BEARING ID.	LOAD	DESCRIPTION OF TEST
	A1	1	BREAK-IN
1	A2	2	BREAK-IN
	A3	2	BREAK-IN
	B1	1	BREAK-IN
2	B2	2	BREAK-IN
	B3	2	BREAK-IN
	C1	1	BREAK-IN
3	C2	2	BREAK-IN
	C3	2	BREAK-IN
	A1	1	CONCENTRATION
4	A2	2	CONCENTRATION
	A3	2	CONCENTRATION
	A4	1	PARTICLE SIZE
5	A5	2	PARTICLE SIZE
	A6	2	PARTICLE SIZE
	A7	1	PARTICLE SIZE
6	A8	2	PARTICLE SIZE
	A9	2	PARTICLE SIZE
	A10	1	PARTICLE SIZE
7	A11	2	PARTICLE SIZE
	A12	2	PARTICLE SIZE
	B1	1	PARTICLE SIZE
8	B2	2	PARTICLE SIZE
	B3	2	PARTICLE SIZE
	C1	1	PARTICLE SIZE
9	C2	2	PARTICLE SIZE
	C3	2	PARTICLE SIZE
	A13	1	CONTAMINANT COMPOSITION
10	A14	2	CONTAMINANT COMPOSITION
	A15	2	CONTAMINANT COMPOSITION

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E. FLUID SAMPLING. Since the determination of wear rates of the test components will be based upon Ferrographic analysis and particle counting, extraction of a fluid sample is a critical part of the test procedure. Fluid samples would be removed from the test system on a periodic basis during each contamination exposure. This will permit an accurate evaluation of the wear rates caused by the contaminant throughout the exposure period. The sample schedule will be established to demonstrate this phenomenon. Due to the loss of contaminant effectiveness, the bearing wear rates are expected to decrease with time during the exposure period. Ferrographic analysis and particle counting will allow assessment of the actual wear debris generated as well as the overall contaminant level exposed to the test component.

F. STRESS FACTOR. The effect of the contamination level, load, and speed combination will be evaluated during these tests. An appropriate stress factor (load, speed, etc.) must be established experimentally. A stress factor similar to that used on ball bearing tests conducted by SKF Industries for the Naval Air Engineering Center may be a suitable candidate for the particulate contaminant wear testing [49]. The load and speed used in the SKF tests far exceeded the recommended ratings of the bearings tested; however, the actual life measured from these tests far exceeded the predicted L_{10} life for the stress factor used. It is expected that particulate contaminants used in controlled bearing tests will also induce wear at an acceptable rate for appraisal purposes. This method of wear acceleration has been used with excellent results in other contaminant sensitivity tests at the Fluid Power Research Center (FPRC).

G. ADDITIONAL PARAMETER MONITORING

1. Appropriate performance parameters will be monitored on each test component. An accelerometer with signal conditioning circuitry and a graphical recorder or oscilloscope combination will be used for vibration monitoring. The accelerometer position will be determined experimentally with each component type. Temperature will be monitored in two ways, lubricant temperature (upstream and downstream) on every component and/or directly on the test component. Backlash in gear tests could be measured by means of shaft rotation. Reciprocating seal leakage will be monitored with periodic compression tests.

2. In testing ball bearings, specifically, temperature and vibration will be monitored performance parameters. An accelerometer will be mounted directly onto the bearing housing. The accelerometer type (directional, frequency, and sensitivity) is presently under consideration with assistance from the electronic and acoustics personnel at the Fluid Power Research Center. Thermocouples will be in direct contact with the outer race of the test bearing at the loaded area on the race. The placement of thermocouples on the outer race of rolling-element bearings has been utilized with valuable results in several bearing temperature analyses [50].

IX. TEST RESULT EVALUATION

A. The objective of this project is to evaluate the influence of particulate contaminants on wear rates of oil-wetted components. The primary objective of the testing will be to correlate wear rates with particulate contaminants, the secondary objective being to correlate the wear rates with the wear-related performance parameters. Data from the component tests will include particulate contamination levels, debris generation, and performance parameters. Evaluation of the parameter degradation will permit more than a correlation between wear debris generation and contamination levels. This additional evaluation will involve the correlation between wear debris concentration and performance. It is felt that the basis of any tribology effort should be the correlation between wear and performance.

B. Another objective of this project, the correlation of particulate contamination with wear, will be approached by a wear debris analysis program. The particulate contamination rate being influenced by the concentration, size range, and composition. Ferrographic analysis of the samples taken throughout each contaminant exposure will provide wear rate data and an indication of the wear particle origins. The wear rates will be determined from the difference in the amount of particles generated from sample to sample. That is, a sample taken two minutes after the initial 0-5 μM particle injection would be compared to the four-minute sample in order to determine the amount of particles generated with respect to time.

C. In addition to the determination of the amount of generated particles, there will be a microscopic analysis of the Ferrograms. That is, the Ferrographic slides will be subject to an objective visual analysis by the Ferrographer. The origins of the particles can be distinguished by the Ferrographer. That is, composition and wear type can be determined. In the case of the ball bearing tests, since the composition of the races and the balls is the same, the wear type would be the distinct parameter of the generated particle. The wear type can be distinguished by consideration of the shape and color. For example, a jagged metallic particle would be a fatigue chunk; whereas, a spiral-shaped or crescent-shaped metallic particle would be considered a cutting wear particle. The two modes of Ferrographic analysis described have been used with excellent results at the Fluid Power Research Center [6].

D. Performance parameter data, vibration and temperature in the case of the ball bearing tests, will also be obtained in addition to particle generation and particulate contamination data. The secondary evaluation will be the correlation of performance with wear rates. That is, performance changes will be analyzed with respect to wear rates as determined Ferrographically.

X. CONCLUSIONS

A. Critical wear components are utilized in practically all power transforming fluid circuits. These components all require some type of lubrication system. Not only does the lubricant function as a separating film and heat transfer medium, it also transports harmful particulate contaminants throughout the system. The effect of these generated, ingested, and residual particles on critical wear surfaces is, in general, to accelerate wear rates and reduce useful life.

B. A considerable amount of effort has been expended upon the study of contaminant effects on the life and operation of hydraulic systems. This work has led to the development of a contaminant control balance for such systems. While this balance serves well for any fluid system, the application of it to oil-wetted components is difficult. Previous investigations indicate that the presence of particles in the oil of a lubrication system has deleterious effects. However, the nature of the problem has not been documented to a usable extent. The effect of a contaminant on all elements of a lubrication-type system must be quantified in an orderly manner.

XI. RECOMMENDATIONS

A. A study of the contaminant effects on all elements of lubrication-type systems is mandatory in order that allowances in design, application, and maintenance may be made. (It is felt that the knowledge gained from contaminant sensitivity studies at the Fluid Power Research Center on hydraulic components provides a strong background for the study of critical wear components in lubricated systems.)

B. The first phase of effort for a much needed oil-lubricated component wear study would be the vast literature search reported herein. The second phase, which should naturally follow, would include the testing of critical wear components under load with a particulate contaminated lubricant. Data obtained from these tests would include wear particle analysis and various performance parameter degradations. (Extensive studies on contaminant sensitivity of hydraulic components at the Fluid Power Research Center complemented by the information gathered in the literature search will provide the background necessary to successfully analyze the data obtained from the lubricated component tests. It is felt that there is a true potential for useful correlations leading to a better understanding of the effect of particulate contaminants on wear in oil-lubricated components.)

C. It is recommended that the effort outlined in this report be implemented. The first component to receive close study would be the ball bearing. The work would be followed by a study of roller bearings, gears, and sliding elements. The concluding investigation then would encompass a system analysis where more than one component is involved.

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